

Al/Al₂O₃ Metal Matrix Composites (MMCs) and Macrocomposites for Armor Applications

**by Prashant Karandikar, Eric M. Klier, Matthew Watkins,
Brandon McWilliams, and Michael Aghajanian**

ARL-RP-460

September 2013

*A reprint from Proceedings of the 37th International Conference and Exposition on Advanced
Ceramics and Composites (ICACC),
Daytona Beach, FL, 27 January–1 February 2013.*

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5069

ARL-RP-460**September 2013**

Al/Al₂O₃ Metal Matrix Composites (MMCs) and Macrocomposites for Armor Applications

Prashant Karandikar, Matthew Watkins, and Michael Aghajanian
M Cubed Technologies, Inc.

Eric M. Klier and Brandon McWilliams
Weapons and Materials Research Directorate, ARL

A reprint from *Proceedings of the 37th International Conference and Exposition on Advanced
Ceramics and Composites (ICACC)*,
Daytona Beach, FL, 27 January–1 February 2013.

| REPORT DOCUMENTATION PAGE | | | | Form Approved OMB No. 0704-0188 | |
|--|-----------------------------|------------------------------|---|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS. | | | | | |
| 1. REPORT DATE (DD-MM-YYYY) September 2013 | | 2. REPORT TYPE Reprint | | 3. DATES COVERED (From - To) 27 March 2012–26 March 2013 | |
| 4. TITLE AND SUBTITLE Al/Al ₂ O ₃ MMCs and Macrocomposites for Armor Applications | | | | 5a. CONTRACT NUMBER W911NF-11-2-0040 | |
| | | | | 5b. GRANT NUMBER | |
| | | | | 5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S) Prashant Karandikar,* Eric M. Klier, Matthew Watkins,* Brandon McWilliams, and Michael Aghajanian* | | | | 5d. PROJECT NUMBER | |
| | | | | 5e. TASK NUMBER | |
| | | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-WMM-F Aberdeen Proving Ground, MD 21005-5069 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER ARL-RP-460 | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT U.S. Army Research Laboratory ATTN: RDRL-WMM-F Aberdeen Proving Ground, MD 21005-5069 | | | | | |
| 13. SUPPLEMENTARY NOTES A reprint from <i>Proceedings of the 37th International Conference and Exposition on Advanced Ceramics and Composites (ICACC)</i> , Daytona Beach, FL, 27 January–1 February 2013. *M Cubed Technologies, Inc., Tralee Industrial Park, Newark, DE 19711 | | | | | |
| 14. ABSTRACT Metal matrix composites (MMCs) combine the desirable characteristics of metals (ductility and thermal conductivity) and ceramics (high hardness, high stiffness, low thermal expansion). In this study, Al/Al ₂ O ₃ MMCs with alumina particle contents ranging from 12% to 46% were fabricated by different processing approaches. Microstructures and properties (density, elastic modulus, tensile strength, ductility–failure strain, and thermal expansion) of these MMCs were characterized. Al/Al ₂ O ₃ MMCs showed higher ductility than Al/SiC MMCs. As the measured ductility was still less than that necessary for multi-hit armor applications, a macrocomposite concept was developed. This concept uses incorporation of high-strength, higher-CTE (coefficient of thermal expansion) ductile macroscopic reinforcements in the MMC to induce residual compressive stress in the MMCs with an intent of enhancing ductility. Numerical modeling on an example macrocomposite system showed that residual compressive stresses can indeed be generated. Specimens were designed to test the numerical predictions and generate data for designing a macrocomposite system. A process was developed and applied successfully to fabricate the macrocomposite specimens. | | | | | |
| 15. SUBJECT TERMS armor, MMC, encapsulant, hardness, ductility, stiffness, lightweight | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT UU | 18. NUMBER OF PAGES 18 | 19a. NAME OF RESPONSIBLE PERSON Eric M. Klier |
| a. REPORT Unclassified | b. ABSTRACT Unclassified | c. THIS PAGE Unclassified | | | 19b. TELEPHONE NUMBER (Include area code) 410-306-0741 |



Al/Al₂O₃ MMCs AND MACROCOMPOSITES FOR ARMOR APPLICATIONS

| | |
|-------------------------------|--|
| Journal: | <i>37th Int'l Conf & Expo on Advanced Ceramics & Composites (ICACC 2013)</i> |
| Manuscript ID: | 1457783.R1 |
| Symposium: | Symposium 4: Armor Ceramics |
| Date Submitted by the Author: | n/a |
| Complete List of Authors: | Karandikar, Prashant; M Cubed Technologies, |
| Keywords: | |
| | |

SCHOLARONE™
Manuscripts

Al/Al₂O₃ MMCs AND MACROCOMPOSITES FOR ARMOR APPLICATIONS

P. Karandikar^{*1}, E. Klier², M. Watkins¹, Brandon McWilliams², and M. Aghajanian¹

¹M Cubed Technologies, Inc.
1 Tralee Industrial park
Newark, DE 19711

²U.S. Army Research Laboratory
ATTN: RDRL-WMM-F
Bld. 4600, 1016
APG, Maryland 21005-5069

ABSTRACT

Metal matrix composites (MMCs) combine the desirable characteristics of metals (ductility and thermal conductivity) and ceramics (high hardness, high stiffness, low thermal expansion). In this study, Al/Al₂O₃ MMCs with alumina particle contents ranging from 12% to 46% were fabricated by different processing approaches. Microstructures and properties (density, elastic modulus, tensile strength, ductility – failure strain, and thermal expansion) of these MMCs were characterized. Al/Al₂O₃ MMCs showed higher ductility than Al/SiC MMCs. As the measured ductility was still less than that necessary for multi-hit armor applications, a macrocomposite concept was developed. This concept utilizes incorporation of high strength, higher-CTE (coefficient of thermal expansion) ductile macroscopic reinforcements in the MMC to induce residual compressive stress in the MMCs with an intent of enhancing ductility. Numerical modeling on an example macrocomposite system showed that residual compressive stresses can indeed be generated. Specimens were designed to test the numerical predictions and generate data for designing a macrocomposite system. A process was developed and applied successfully to fabricate the macrocomposite specimens.

INTRODUCTION

A variety of materials are used for the construction of armor for personnel, vehicles, and aircraft. Properties of some of the most commonly used armor materials are summarized in Table 1. Depending on the projectile to be defeated, one or more of these materials are needed in the form of a “system”. The components of the system have to work synergistically to achieve projectile defeat. For example, many of the current armor solutions require a combination of a ceramic to blunt the projectile and a ductile backing to catch the fragments^{1,2}. For multi-hit requirements, ceramics are typically used as a mosaic of tiles or cylinders¹. Two examples of the use of an array or mosaic of ceramics are (a) ceramic cylinders in a polymeric matrix (e.g. LIBA, SURMAX, SMART armor)¹ with or without a metal backing, and (b) SiC tiles encapsulated in titanium (Ti) produced by hot pressing¹. One critical aspect of the encapsulation approach is the prevention of cracking in the ceramic due to the CTE mismatch-induced residual stresses. In the Ti-SiC system¹, residual compressive stresses are generated in the ceramic due to the higher CTE metal surrounding it. This residual stress increases dwell, and the confined ceramic debris provides the erosive phase of projectile defeat.

Table 1. Summary of properties of typical armor materials

| Material | ρ (g/cc) | E (GPa) | σ (MPa) | K_{IC} (MPa-m ^{1/2}) | Elongation (%) | Hardness | AD (psf) [†] | CTE ppm/K |
|---|------------------|------------|-------------------|-------------------------------------|-------------------|----------|--------------------------|--------------|
| UHMWPE Spectra 2000 | 0.97 | 124 | 3340* | N/A | 3 | N/A | 5.0 | 100 |
| 5083 Al –H32 | 2.66 | 72 | 320* | 43 | 17 | 54 RB | 13.8 | 25 |
| RHA | 7.86 | 207 | 1110* | 75 | 14 | 99 RB | 40.9 | 13.2 |
| Mild Steel 1018 | 7.8 | 210 | 634 | 40 | 27 | 120B | 40.6 | 13.4 |
| 304 SS (annealed) | 8.03 | 200 | 490 | 88 | 40 | 201B | 41.6 | 16.6 |
| Ti-6-4 | 4.43 | 114 | 940* | 60 | 16 | 334B | 23.0 | 10.6 |
| Al ₂ O ₃ CAP-3 | 3.90 | 370 | 379 | 4-5 | 0.10 | 1292 | 20.2 | 6.0 |
| Hot Pressed B ₄ C Ceralloy-546 4E | 2.50 | 460 | 410 | 2.5 | 0.09 | 2066 | 13.0 | 5.1 |
| Hot Pressed SiC-N | 3.22 | 453 | 486 | 4.0 | 0.10 | 1905 | 16.7 | 3.0 |
| Sintered SiC Hexoloy | 3.13 | 410 | 380 | 4.6 | 0.09 | 1924 | 16.2 | 3.0 |
| SiC (RBSC) | 3.03 | 380 | 260 | 4.0 | 0.07 | 1332 | 15.7 | 2.9 |
| B ₄ C/Si (RBBC) | 2.56 | 390 | 271 | 5.0 | 0.07 | 1626 | 13.3 | 4.8 |
| TiB ₂ Ceralloy 225 | 4.50 | 540 | 265 | 5.5 | 0.05 | 1849 | 23.4 | 8.1 |

ρ – density; E – Young's modulus; σ – flexural/tensile* strength; K_{IC} – fracture toughness; Hardness for metals Rockwell B or Brinell, for ceramics - Knoop 2kg; AD – areal density, CTE – coefficient of thermal expansion (20-100°C)

Sources: Spectra: Honeywell; CAP-3: CoorsTek; Ceralloy, Ekasic-T: Ceradyne; Hexoloy: Saint Gobain; SiC-N: Cercom (CoorsTek); RBSC, RBBC: M Cubed Technologies (MCT). Properties for other manufacturer's materials are from their respective websites/datasheets except for 2kg Knoop hardness [†]Areal density (lb/sf -psf): weight of 12 x 12 x 1 inch panel in pounds

Aluminum and aluminum based MMCs could offer a lower-cost alternative (to HIPed Ti) for encapsulation of ceramic tiles for armor applications. MMCs combine the desirable characteristics of metals (ductility, thermal conductivity) and ceramics (high hardness, high stiffness, low thermal expansion). In addition, the CTE of MMCs can be tailored to match more closely to the CTE of the ceramic being encapsulated. This would lower the residual stresses and reduce the potential for cracking of the ceramic or encapsulating material and warping of the macro composite during processing.

Aluminum-SiC particulate MMCs (Al/SiC)⁴⁻⁵ have been used successfully in a variety of applications in large tonnage. Al/SiC MMCs also provide desirable properties for armor applications (high hardness, high stiffness, and light weight). However, for SiC-based MMCs, matrix Al has to be alloyed with Si (>8%) to prevent formation of the deleterious Al₄C₃. Unfortunately, Si alloying reduces the ductility of the alloy and the MMC. For most armor applications, ductility of the encapsulant material is very critical for achieving multi-hit capability. If the SiC particulates are replaced with Al₂O₃ particulates, the requirement for Si in the matrix alloy is eliminated and more ductile matrix alloys can be selected. As a result, an MMC with higher ductility can be achieved.

Liu et al.^{6,7} have reported on the effect of superimposed hydrostatic pressure on deformation and fracture of Al/Al₂O₃ MMC (15% particles). At 300 MPa of superimposed pressure, the reduction in area changed from 10% to 80% and the failure strain was quadrupled. Thus, very significant increase in ductility was achieved. The main mechanism for ductility increase was suppression of void generation and cracking of the alumina particles.

In this work, Al/Al₂O₃ MMCs with various alumina contents were made. Properties of these were characterized. To further enhance multi-hit capability of the MMC-based armor solution, a macrocomposite concept was developed. In this concept, a higher-CTE (higher CTE than the CTE of the

MMC), high-ductility material, such as austenitic stainless steel in the macroscopic form (wire, sheet, expanded sheet, perforated sheet, corrugated sheet, 3-D structure, etc.), is incorporated in the MMC to induce residual compressive stresses and further increase its ductility. Numerical modeling was conducted on an example system to assess if residual compressive stresses can be generated. Specimens were designed to test the numerical predictions and assess the effect on MMC ductility. Processes were developed and applied successfully to fabricate the macrocomposite test specimens.

EXPERIMENTAL PROCEDURE

MMC plates (150 mm x 200 mm x 6 mm) with varying alumina reinforcement content from 12 to 46% were produced by a casting technique. Two different types of matrix alloys were used: Al-4Mg and Al-1Mg-0.6Si-0.4Cu. For comparative evaluation, plates were also cast out of 170.1 aluminum alloy and 170.1 + 4Mg alloy. Wetting between ceramic particles and the matrix was achieved by either mechanical means or chemical means (PRIMEX³). Small samples were cut from these MMCs, potted, and polished for microstructural observations. Tensile test samples and CTE measurement samples were machined from the composite plates. Tensile testing was conducted on flat dog-bone shaped specimens (ASTM B557). For each plate 5 tensile specimens were tested and average values were reported. CTE testing was conducted on 5 x 5 x 25 mm sample using a Netzsch TMA 402 F1 at a heating rate of 5°C/minute from -20°C to 500°C with a helium purge gas. The system influence (sample holder expansion) was corrected by a calibration measurement of a fused silica standard. The calibration run was carried out under the same conditions as used for the test samples. Measurements were made on two samples for each material and an average value was reported. In all cases both samples showed similar/reproducible results.

PROPERTIES OF Al/Al₂O₃ MMCs

Microstructures of Al/Al₂O₃ MMCs with various reinforcement contents are shown in Figure 1. The microstructures clearly show the different alumina particle contents in the different MMCs. The matrix alloy, alumina volume fraction, densities, mechanical properties, and thermal properties are summarized in Table 2. Mechanical and thermal properties are plotted in Figures 2-6. Mechanical property data for the Al/SiC MMCs (Al-10Si matrix) are also included for comparison^{4,5}. The data in Figures 2 through 6 shows that elastic modulus and strength increase with Al₂O₃ volume fraction. Failure strain (elongation), on the other hand, decreases as the Al₂O₃ volume fraction is increased. Failure strain is also dependent on the matrix alloy selection. As is well known^{4,5}, elastic modulus does not follow the rule of mixtures (linear increase with particle volume fraction) for particulate MMCs. The coefficient of thermal expansion (CTE) decreases as the alumina particle content is increased.

Al/Al₂O₃ MMCs with Al-1Mg-0.6Si-0.4Cu matrix showed the highest failure strain, followed by Al/Al₂O₃ MMCs with Al-4Mg matrix, and the Al/SiC MMCs with Al-10Si alloy matrix showed the lowest failure strain. The failure strain of Al/Al₂O₃ was still lower than that desired for armor applications, especially as encapsulants for ceramic tiles. Therefore, other means of increasing the ductility of MMCs were explored.

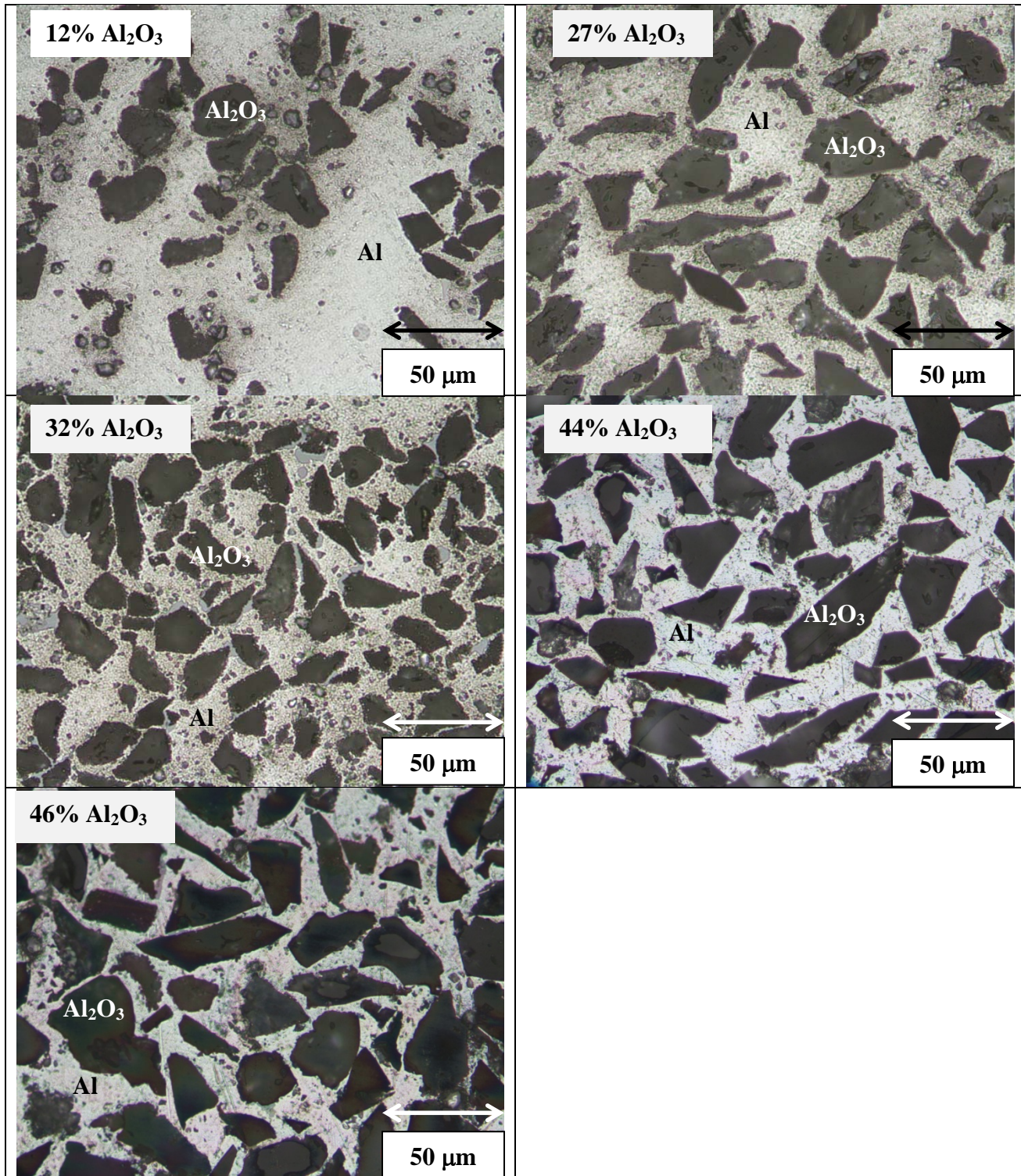


Figure 1. Microstructures of the Al/Al₂O₃ composites with different particulate loadings.

Table 2. Properties of Al/Al₂O₃ MMCs and their comparison with properties of Al/SiC MMCs (as cast)

| Material (as cast) | Matrix | ρ (g/cc) | Vp | E (GPa) | UTS (MPa) | e_f (%) | CTE (ppm/K) 20-500°C | CTE (ppm/K) 20-100°C |
|-----------------------------------|-------------------------|------------------|------|------------|----------------|--------------|----------------------------|----------------------------|
| 170 Alloy | N/A | 2.71 | 0 | 71 | 99.1 \pm 21 | 30 | 26.5 | 22.4 |
| 170 + 4 Mg | N/A | 2.63 | 0 | 69 | 171.0 \pm 25 | 24 | -- | -- |
| Al/Al ₂ O ₃ | Al 1Mg- 0.6Si-0.4-Cu | 2.85 | 0.12 | 87 | 111.8 \pm 7 | 1.40 | -- | -- |
| Al/Al ₂ O ₃ | Al-Mg | 3.05 | 0.27 | 114 | 103.6 \pm 19 | 0.70 | 20.4 | 16.3 |
| Al/Al ₂ O ₃ | Al 1Mg- 0.6Si-0.4-Cu | 3.12 | 0.32 | 127 | 149.6 \pm 8 | 0.96 | 17.5 | 14.9 |
| Al/Al ₂ O ₃ | Al-4Mg | 3.27 | 0.44 | 147 | 168.6 \pm 25 | 0.30 | 14.1 | 11.2 |
| Al/Al ₂ O ₃ | Al-4Mg | 3.30 | 0.46 | 160 | 174.3 \pm 9 | 0.51 | 14.1 | 11.2 |
| Al/SiC | Al-10Si | 2.78 | 30 | 120 | 206.8 \pm 19 | 0.18 | -- | 15.6 |
| Al/SiC | Al-10Si | 2.96 | 55 | 202 | 128.1 \pm 28 | 0.09 | -- | 11.8 |

ρ – density, Vp – particle volume fraction, E – Elastic Modulus, UTS – ultimate tensile strength, e_f – failure strain, CTE – coefficient of thermal expansion. All properties are in the as-cast (F) condition.

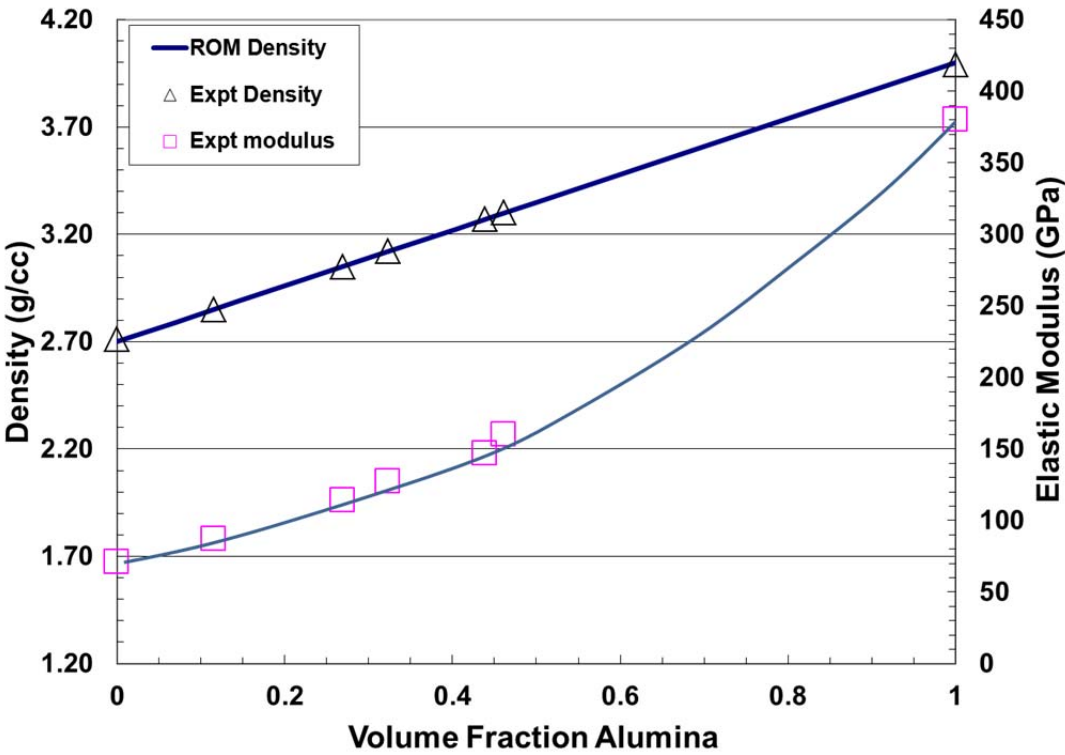


Figure 2. Density and Elastic modulus plot for as-cast Al/Al₂O₃ MMCs.

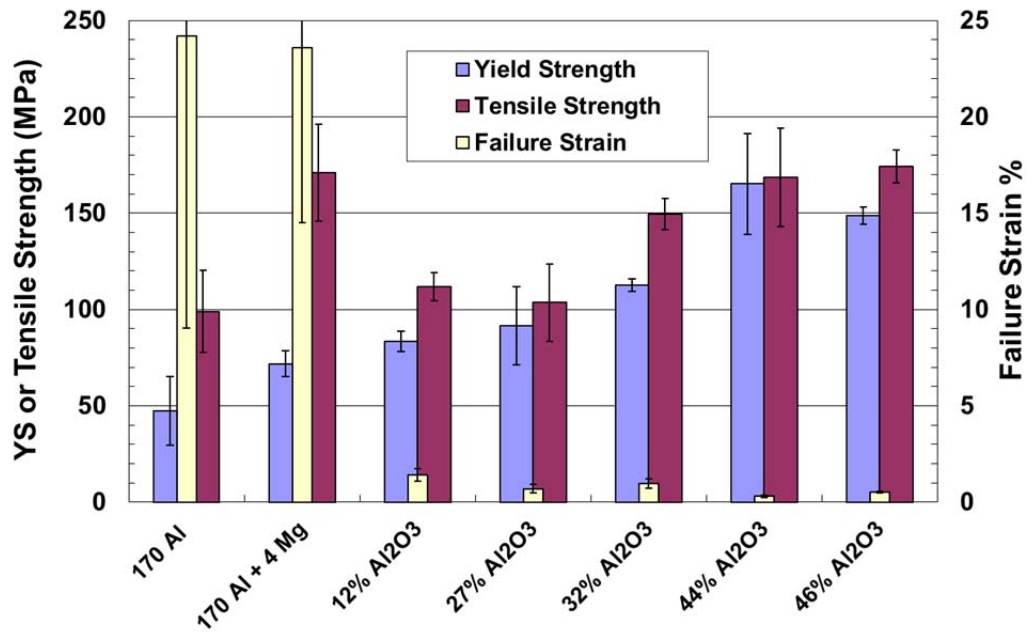


Figure 3. Yield strength, ultimate tensile strength, and failure strain plot for as-cast Al/Al₂O₃ MMCs and base alloys.

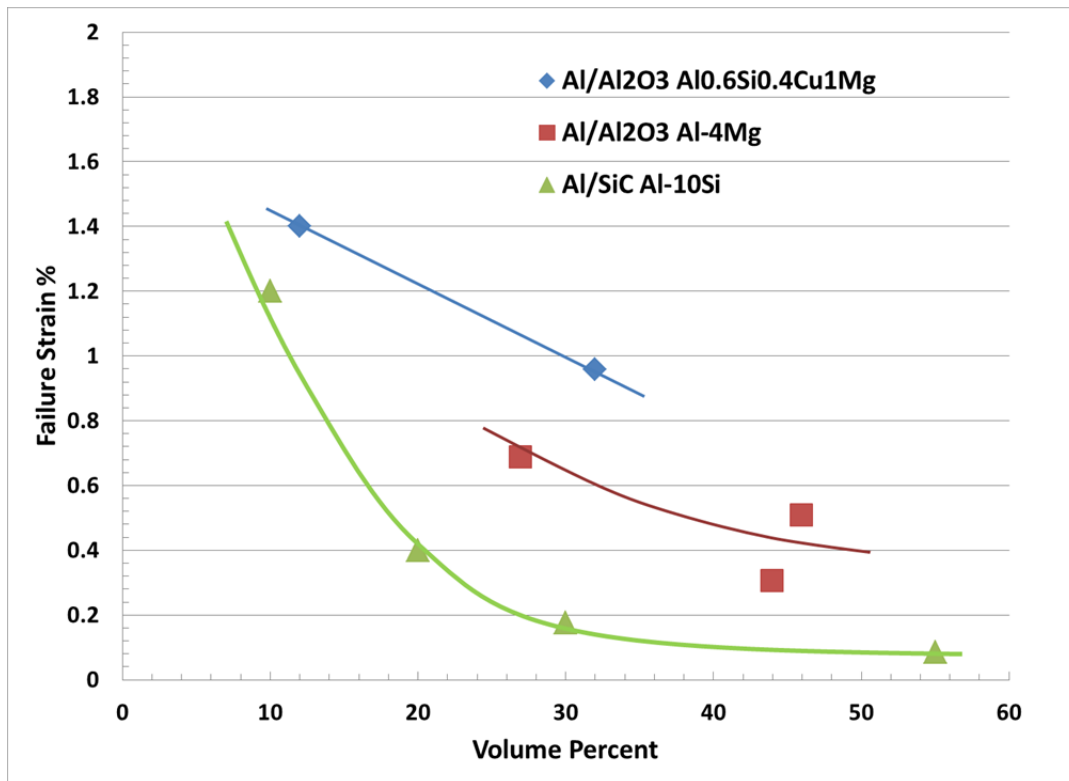


Figure 4. Effect of ceramic content and matrix material on failure strain of as-cast MMCs.

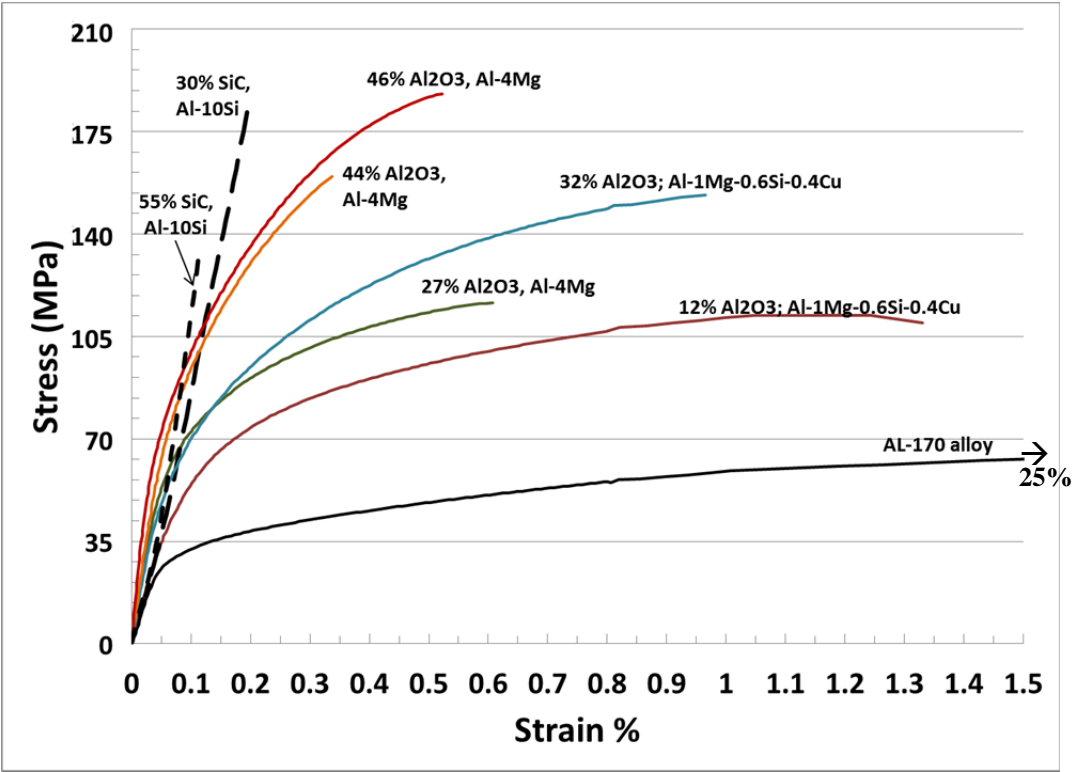


Figure 5. Stress strain curves for as-cast Al/Al₂O₃ and Al/SiC MMCs with various particle contents.

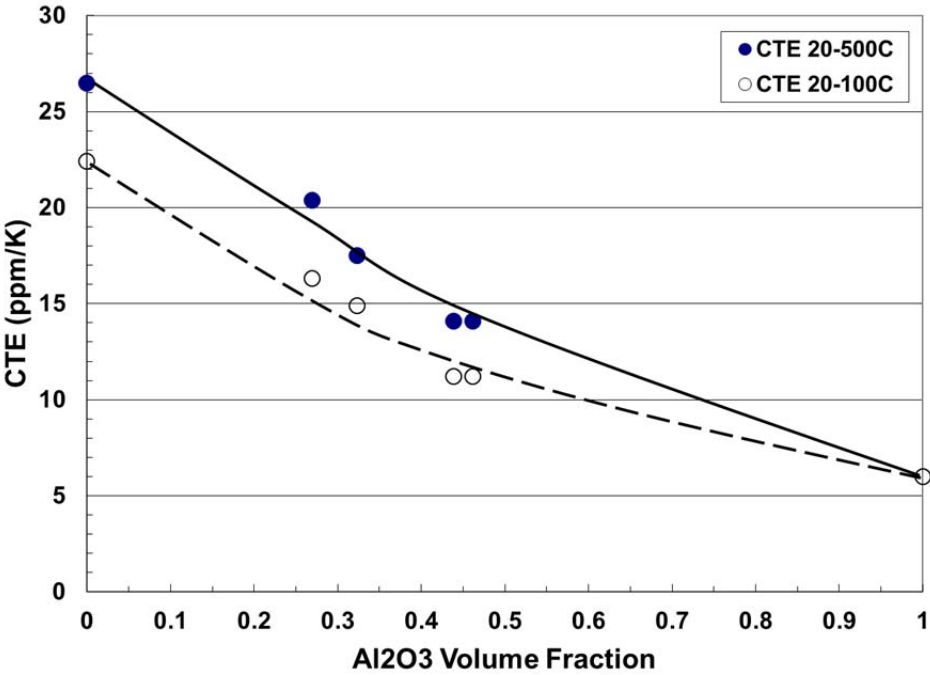


Figure 6. Coefficient of thermal expansion (CTE) plot for as-cast Al/Al₂O₃ composites.

DESIGN OF A MACROCOMPOSITE SYSTEM

Although the Al/Al₂O₃ MMC had higher failure strain than Al/SiC MMC, Al/Al₂O₃ MMC plates broke up into multiple pieces after the first projectile impact and then were unable to stop the subsequent impacts. Thus the failure strain of Al/Al₂O₃ was found to be lower than that desired for obtaining multi-hit capability. Therefore, other means of increasing the ductility of MMCs were explored. Work of Liu et al.^{6, 7} indicates that when 300 MPa superimposed hydrostatic pressure was applied to Al/Al₂O₃ MMC (15% particles) the failure strain (a measure of ductility) was quadrupled.

Based on this result, a macrocomposite concept was developed. Here, a third component is added to the Al-MMC/ceramic tile system with higher CTE than that of the MMC and high tensile strength, to put the MMC (and ceramic tiles) under a residual compressive stress after fabrication. An exhaustive search was conducted to identify appropriate reinforcement materials. Since the MMC processing is done with the ductile reinforcement in place, the reinforcement must withstand the MMC processing temperature (~750°C). In addition, resistance to molten Al is desired. Several materials were identified with higher CTEs and the requisite temperature capability and reaction resistance (e.g. austenitic stainless steels, Carpenter 21Cr-6Ni-9Mn alloy). Thus the macrocomposite system will include three materials with successively higher CTEs: a ceramic, an encapsulating MMC, and a constraining higher CTE reinforcement. The reinforcement can be in the form of a wire, sheet, expanded sheet, corrugated sheet, 3D periodic structure etc. to provide complete constraint and residual compression.

NUMERICAL MODELING OF AN EXAMPLE MACROCOMPOSITE SYSTEM

Numerical modeling was undertaken on an example system to calculate the residual stresses. Also, the relative amounts of the MMC and steel were varied to assess the ability to vary the residual stress. The system that was analyzed consisted of two concentric cylinders: MMC on the inside and steel on the outside. For this analysis, perfect bonding was assumed between the steel and the MMC. The MMC diameter was assumed to be 6.35 mm and the steel thickness was varied from 1.27 mm to 5.08 mm. The MMC was assumed to be Al/SiC with 55% particulates (Density = 2.96 g/cc, E = 202 GPa, CTE = 11.8 ppm/K). Steel with the following properties was used as the constraint layer: Density = 7.8 g/cc, E = 210 GPa, CTE = 19.1 ppm/K). The temperature difference from the processing temperature to room temperature was assumed to be 400°C. Figure 7 shows the results of this analysis.

The analysis predicted that compressive stresses in the range of ~100 to 260 MPa can be generated in the MMC due to the steel reinforcement. Similar stresses are expected to be generated in the Al/Al₂O₃-steel macrocomposite system. Based on the work of Liu et al. described earlier, this stress range is sufficient to increase the ductility of the MMC. Therefore, design and fabrication of a macrocomposite test specimen to verify these predictions was undertaken.

DESIGN AND FABRICATION OF MACROCOMPOSITE SPECIMENS

To experimentally assess the effect of residual compressive stress on the ductility of the MMC, an MMC-steel tensile macro composite specimen was designed. A schematic of this specimen is shown in Figure 8. The specimen consists of a standard tensile test bar for metallic materials per ASTM B 577M-07. The outer shell of the specimen consists of a reinforcing steel alloy tube which is filled with the MMC. The residual stress is systematically varied by selecting the following parameters:

- MMC Type (different MMCs have different CTEs - see Table 2)
- Constraining alloy type: AISI 1018 mild steel (low CTE – 13.4 ppm/K) and 304 stainless steel (high CTE – 16.6 ppm/K) – see Table 1
- Three different ratios of MMC diameter (d_{mmc}) to confining metal diameter (d_c)

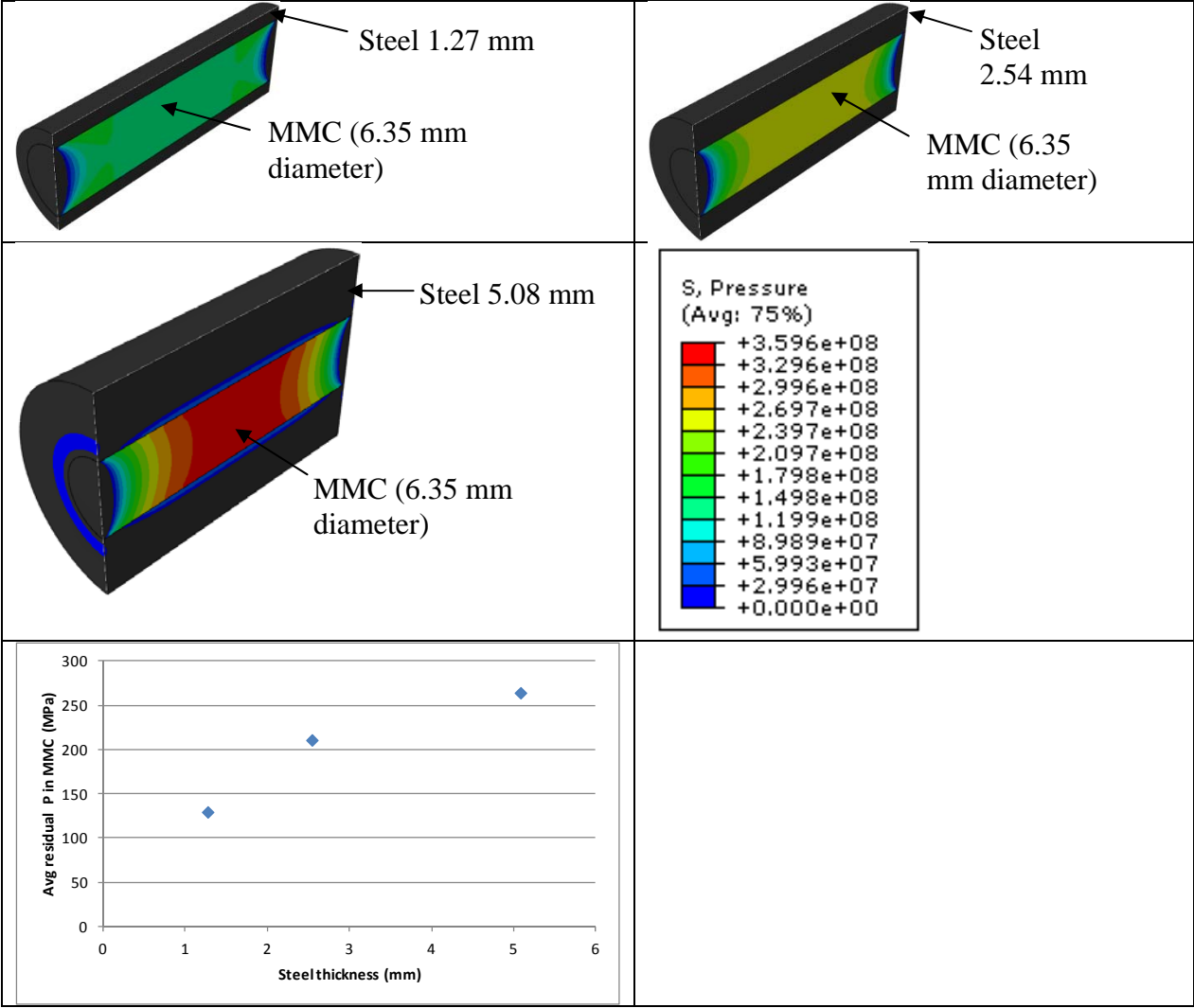


Figure 7. Prediction of residual stresses in the MMC due to steel confinement/reinforcement.

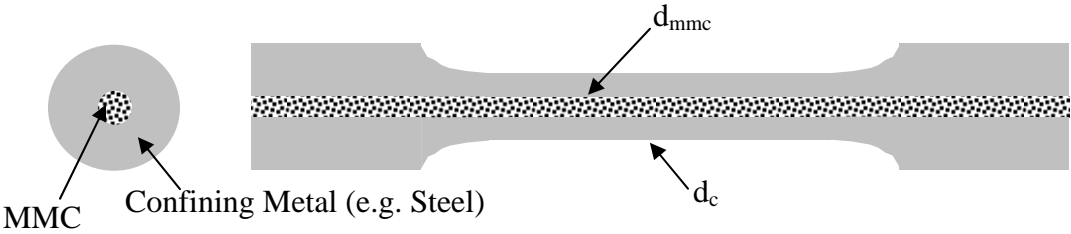


Figure 8. Design of a tensile test sample to evaluate mechanical behavior of MMCs under compressive stress generated by confinement (based on ASTM B557M-07).

A manufacturing process was developed to fabricate the macrocomposite tensile specimens. This process was applied successfully to fabricate the macrocomposite specimens as shown in Figure 9. Future work will include mechanical testing of these specimens, numerical modeling, and analysis of the

results. These data will be used to assess whether we can achieve synergistic effect by combining dissimilar materials at this length scale.

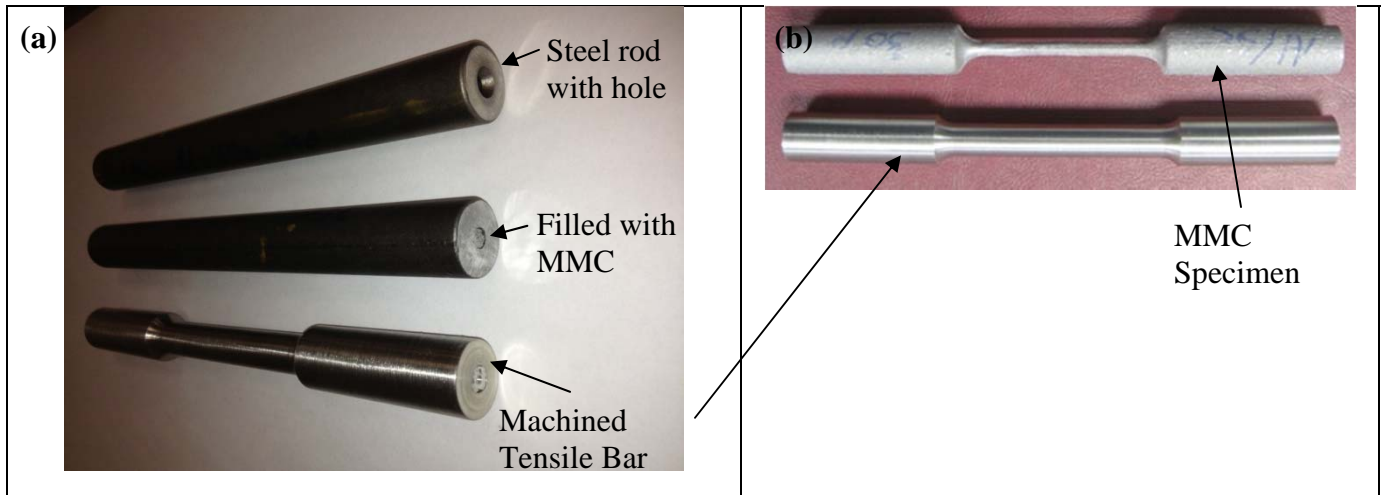


Figure 9. (a) Steel rod with hole for casting macro-composite tensile bars, (b) Steel rods with MMC cast in the center, (c) Macro-composite tensile specimen after machining (left) and as-cast MMC dog bone specimen (right).

The bonding between the cast MMC and the constraining steel layer is also critical for generating the residual compressive stress in the MMC. To evaluate the bonding between the steel and the MMC and the effects of the parameters listed in the previous section, a push-out-type shear specimen was designed as shown in Figure 10a. Again, a fabrication process was developed to make the shear specimens. Using this process, several specimens with different MMC types, steel types, and steel/MMC ratios were successfully fabricated (Figure 10b). Future work will include mechanical testing of these specimens, numerical modeling, and analysis of the results.

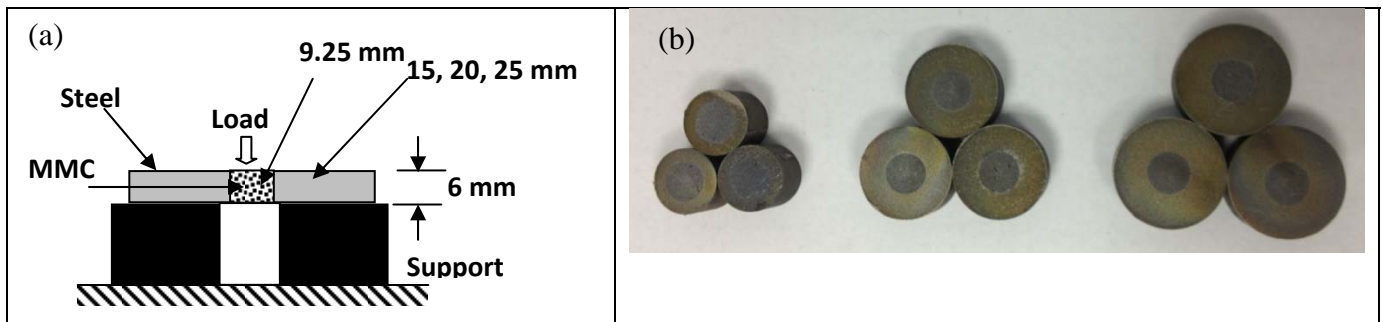


Figure 10. (a) A schematic of the cross-section of a concentric cylinder specimen for measuring steel-MMC bond strength (b) Photo of the specimens fabricated.

SUMMARY AND CONCLUSIONS

Al/Al₂O₃ MMCs with varying alumina content were produced successfully. Characterization of Al/Al₂O₃ MMCs with varying alumina contents showed that density, elastic modulus, and strength

increased with increased particle content. Failure strains (ductility), on the other hand, decreased with increasing particle content. Al/Al₂O₃ MMCs with Al-1Mg-0.6Si-0.4Cu matrix showed the highest failure strain, followed by Al/Al₂O₃ MMCs with Al-4Mg matrix, and the Al/SiC MMCs with Al-10Si alloy matrix showed the lowest failure strain. Thus, failure strain was dependent on the matrix purity and extent and type of alloying. The failure strain of Al/Al₂O₃ MMC was lower than that desired for a multi-hit capability, especially as an encapsulant for ceramic tiles.

A literature review of MMCs revealed that under compressive confining pressure, the failure strain (ductility) of MMCs is quadrupled. A macrocomposite system containing high-strength, high ductility, and higher-CTE reinforcement was designed to take advantage of this phenomenon. Numerical modeling of an example system showed that significant confining compressive stress (260 MPa) can be generated in the MMCs due to a higher-CTE ductile reinforcement.

Unit-cell-type macrocomposite tensile and shear specimens were designed to generate the mechanical property data needed to design a macrocomposite system. Fabrication processes were developed and the ability to manufacture the macrocomposite specimens was demonstrated.

Future work will include mechanical testing of these macro-composite specimens, analysis of the data, and numerical modeling. The results obtained will be useful in assessing whether we can achieve synergistic effect by combining dissimilar materials at this length scale.

ACKNOWLEDGEMENT

This work was funded by a Co-operative Agreement No. W911NF-11-2-0040 with the US Army Research Laboratory (ARL), APG, MD.

REFERENCES

- ¹W. A. Gooch, "Overview of the development of ceramic armor technology: past, present and the future," Ceramic Engineering Science Proceedings (CESP), 32 [5] pg. 195-214
- ²P. G. Karandikar, G. Evans, S. Wong, M. Aghajanian, and M Sennett, "A review of ceramics for armor applications," CESP, Vol. 29 [6] (2008), 163-178.
- ³P. G. Karandikar, M. K. Aghajanian, D. Agarwal, and J. Cheang, "Microwave assisted (MASS) processing of metal-ceramic and reaction bonded composites", CESP, Vol. 27, [2] (2007), 435-446.
- ⁴A. Evans, C. San Marchi, and A. Mortensen, Metal Matrix Composites in Industry, Kluwer Academic Publishers, Norwell, MA, USA (2003).
- ⁵B. Givens, W. M. Waggoner, K. Kremer, and M. Aghajanian, "Effect of particle loading on the properties of Al/SiC metal matrix composites," in Aluminum Alloys: Fabrication, Characterization and Applications II, Yin et al. editors, TMS, Warrendale, PA (2009) 197-202.
- ⁶D. Liu and J. J. Lewandowski, "The effects of superimposed hydrostatic pressure on deformation and fracture part I: particulate reinforced 6061 composites", Metallurgical Transactions A 24 [3] (1993) 601-608.
- ⁷D. Liu and J. J. Lewandowski, "The effects of superimposed hydrostatic pressure on deformation and fracture part II: particulate reinforced 6061 composites", Metallurgical Transactions A 24 [3] (1993) 609-614.

NO. OF
COPIES ORGANIZATION

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
DTIC OCA

1 DIRECTOR
(PDF) US ARMY RESEARCH LAB
IMAL HRA

1 DIRECTOR
(PDF) US ARMY RESEARCH LAB
RDRL CIO LL

1 GOVT PRINTG OFC
(PDF) A MALHOTRA

ABERDEEN PROVING GROUND

1 RDRL WMM F
(PDF) E Klier

INTENTIONALLY LEFT BLANK.